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Review

Influence of climate change on protected cultivation: Impacts and sustainable adaptation strategies - A review

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ABSTRACT

The interaction between agriculture, particularly intensive greenhouse horticulture, and climate, is of dual nature. The resources required to produce crops, such as fossil fuel, affect climate change (CC), which, in turn, will backfire with altered growing conditions in the future. For instance, phenomena like heat waves and severe droughts would significantly affect management of protected cultivation systems, which would require adaptation processes. This puts greenhouse vegetable producers under high pressure, as they are required to adopt environmentally friendly production strategies. Here, we provide a comprehensive critical review of the effects of present and future CC scenarios on controlled environment agriculture as well as the mapping of climate protection measures in these environments. We examined published articles from 1990 to 2019, focused mainly on the European region and pinpointing the differences between the temperate North and the Mediterranean basin, although some research works from other regions were also considered. We recommend adaptations in terms of sufficient cooling, and improvement of natural and additional light for winter production. Technical and conceptual innovations such as the semi-/closed greenhouse based on mechanical cooling and dehumidification are discussed along with structural solutions such as passively ventilated greenhouses and screenhouses. Moreover, we recommend adaptation in terms of cultivar selection, greenhouse type, cover material, cultural practices and production technology to cope with abnormal climate alterations and extreme weather conditions associated with CC. We believe that this work will contribute to advance sustainable year-round production.

Contents

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1. Introduction

Nowadays, scientists all over the world agree that the main driving force behind climate change (CC)[1] is overwhelmingly of an anthropogenic origin, with industrial activity as the dominant contributor to the substantial increase in carbon dioxide emissions (Li et al., 2017; Bisbis et al., 2018a; Shuai et al., 2018).

Agriculture/horticulture and CC have a dual interaction. On the one hand CC is affected by agricultural activity, on the other hand the impacts arising will backfire by changing the environmental conditions for agriculture/horticulture. A striking feature of greenhouse production is the large amount of energy consumption for heating, especially in temperate areas and during the cold season. Consequently, high greenhouse gas (GHG) emissions are produced (Gruda et al., 2019). In Europe, apart from the need for plant protection, the risk of nutrient leaching and the turnover of soil organic matter, generally there will be differences between northern and southern regions (Olesen and Bindi, 2002). Since CC is generally associated with globally increased air temperature, it may enable the cultivation of new crop species, a higher crop production and an expansion of suitable areas for crop cultivation in northern Europe. However, in southern areas some disadvantages may predominate. The possible increase in water shortage and extreme weather events will probably cause lower yields, higher yield variability and a reduction in areas suitable for traditional crops production (Olesen and Bindi, 2002). In our opinion, this statement could be generally applied for warmer regions worldwide, even if the local climate specifics and particularities must be considered.

Anticipated climatic changes encourage the expansion of protected agriculture, i.e., greenhouses and screenhouses, within which external climatic effects are restrained. According to Boulard et al. (2011), non-protected cultivation or natural systems like forest or pasture are supposed to be more dependent on climate than protected ones. However, if protected cultivation would be less dependent on local climate conditions, it would still be of concern because the inside climate and energy balance, and consequently the economic models, are deeply impacted by external conditions.

Both approaches: high-tech and simple greenhouses, as well as screenhouses with a passive control of environmental conditions are currently coexisting in worldwide horticulture (Montero et al., 2009). The area of screenhouses and naturally ventilated greenhouses in the Mediterranean region and in countries with mild climate conditions has been constantly increasing (Gruda et al., 2019). Since the CCs will be associated with generally higher temperatures, it is to assume that this trend of increasing area of simple greenhouses with a passive control of environmental conditions will continue in countries with mild winter climates in the near future (Montero et al., 2009). Unforeseeable climate events and the consumer requirements for all year-round ornamental plants and health-promoting plant compounds from fresh vegetables (Gruda, 2019) will enhance the trend of intensive cultivation in temperate areas as well.

Furthermore, adaptation strategies to secure stable yields of high product quality are required. For instance, water saving would become an important consideration in cultivation strategies, e.g. the use of shading screens to restrain CC effects as high air temperature and water scarcity. The use of insect-proof screenhouses may contribute to both increasing the water use efficiency and reducing the application of pesticides which became significantly important for consumers that demand products without pesticide remainders (Bisbis et al., 2018b). Especially, the nutritional quality of vegetables is becoming increasingly important while the market demands an immaculate product which is safe to consume (Gruda 2005, 2019; Gruda et al., 2018). This puts vegetable producers under high pressure as they are obliged to meet the demand of both, market and consumers, while the climate conditions are changing for the worse. Producers will therefore be required to invest in improved management and technology that reduce wastages, by decreasing the share of unmarketable yield.

In temperate regions, greenhouse production is marked by high energy consumption for heating during the cold season, which is associated with high greenhouse gas emission (GHG). In addition to climate control, factors like artificial lighting, the construction itself, the use of growing media, postharvest transport and packaging are of significant environmental concerns (Gruda et al., 2019).

Scientific publications that analyzed the potential risks of CC on agriculture have rapidly increased in the past several decades (Howden et al., 2007; Aleixandre-Benavent et al., 2017; Dong et al., 2018a; Parajuli et al., 2019). In contrast to past research papers, that considered open agriculture, this review deals with protected cultivation. Moreover, knowledge gaps are pointed out to stimulate research in the field of climate change and related impacts on controlled environment agricultural systems.

Gruda et al. (2019) reviewed the impact of protected cultivation on CC and presented some sustainable adaptations to mitigate this impact. However, concerning the impact of CC protected cultivation, only few studies have been conducted so far.

The aim of this paper is to critically review the literature about future climate change and its potential impacts on protected horticulture, addressing environmental factors such as temperature, radiation and air humidity. Furthermore, the paper is focused on adaptation strategies to mitigate the imposed constraints for a sustainable and climate smart cultivation of horticultural products. These are mainly technical innovations in the greenhouse sector which may assist growers to better suit the needs under changing climate.

2. Material and methods

The focus of this study is to expose the impacts of recent/future CC on controlled environment agriculture, particularly on the production, physiology and product quality of protected horticultural crops. Moreover, we reviewed the possibilities for adaptation, to cope well with these impacts. To do so, we conducted a

[1] *Abbreviations*: ATU = air treatment units, CC = climate change, GDP = gross domestic product, GHG = greenhouse gases, RCP = representative concentration pathway, WUE = water use efficiency.

systematic literature review, examining published articles from 1990 to 2018. The comprehensive review is based on literature from temperate regions of Europe as well as on the Mediterranean basin, although sometimes research works from other areas are also considered. The literature search was conducted using the following academic databases: Web of Science Core Collection (WoSC) platform from Clarivate Analytics, Scopus and ScienceDirect from Elsevier, ResearchGate from Berlin, Google Scholar from Google. Several keywords were chosen to obtain a wide number of search results. According to Aleixandre-Benavent et al. (2017), frequency analysis of possible keywords has revealed that the main issues are focused on "CO_2", "adaptation", "models", "temperature", "responses" and "impact". The authors describe that the topic of "adaptation" appears to be one of the most important topics because of the discussion of human-induced CC that is moving towards clear fact-stimulated research on future pathways. The term "impact" arises and points to research addressing the varying effects of CC (Haunschild et al., 2016). Therefore, as it is reported by Gruda et al. (2019, submitted) we searched for several terms related to CC and protected cultivation. In addition to terms described by Gruda et al. (2019), for the present review we searched for "heat waves", "mild winter", "high temperatures", "high CO_2 concentrations", and "water deficiency". The terms were included in quotation marks, in combinations with AND, to guarantee higher precision in the obtained records. The same keywords were used replacing the word "vegetables" with the respective vegetable name (e.g. "heat waves" AND "greenhouse tomato", …).

Based on our research question and review objective, titles and abstracts from nearly 1000 articles were screened and evaluated, before selecting relevant papers. Afterwards, we identified major studies by critically choosing them and excluding articles that are less relevant for the scope of the present review. A major selection criterion was the quantitative nature of the article, where most of the articles chosen for this review have some quantitative aspects. We selected studies including topics on (1) the response of greenhouse vegetables production to changes in temperature, CO_2, and water availability, (2) sustainable adaptation strategies to potential CCs applied in controlled environment agriculture, and (3) reduction of waste in the production process and value chain of horticultural plants. Table 1 gives a concise information, indicating some sources, together with journals and some article examples that we used in the present paper.

3. Results and discussion

3.1. Impacts of climate change on crop production in protected environments

Climate scenarios like the four representative concentration pathways (RCP's), RCP2.6, RCP4.5, RCP6.0 and RCP 8.5 were designed by the scientific community for the IPCC's, Assessment Reports (IPCC, 2013). The future impacts of these CC scenarios on production of greenhouse vegetables are difficult to predict due to the large differences, including drastic changes, as well as more moderate scenarios. However, by studying regional and global climate simulations we can attempt to deduce some possible impacts on greenhouse vegetable production, and the resulting shift of quality which could potentially become reality even in the near future (Table 2).

3.1.1. The impacts of increasing atmospheric CO_2

Carbon dioxide (CO_2) is expected to accumulate in the atmosphere and will increase to a value between 442 ppm (RCP2.6) and 540 ppm (RCP8.5) by mid-century (IPCC, 2013). When growers provide their vegetables with additional CO_2 it usually results in higher yields. More atmospheric CO_2 might reduce input costs for CO_2 fertilization, but it is unlikely that this practice will become unnecessary in the future as plants can benefit from even higher amounts than those predicted; the most pessimistic scenario, the RCP8.5, predicts atmospheric CO_2 concentration of 935 ppm in 2100 (IPCC, 2013). It was shown that under such concentrations, greenhouse yield of eggplant, cucumber and pepper increased compared to a non-enriched greenhouse (Akilli et al., 2000). However, in ventilated greenhouses, the summer time when plants would make the best use of additional CO_2 coincides with the period of most intensive ventilation requirements, making CO_2 enrichment inefficient, and expensive due to losses to the outside (De Zwart, 2012). This is expected to become more pronounced with the projected increase in heat waves, and the concomitant increase in the frequency of required ventilation (Bisbis et al., 2018a,b). Hence the increased atmospheric concentrations of CO_2 may be advantageous for crop production mainly during summer and depending on the prevailing climate scenario. On the other hand, the quality of produce is not always correlated with increased yields. Dong et al. (2018a) reviewed the effect of CO_2 on vegetable quality. The authors conducted a meta-analysis and found that elevated CO_2 concentrations increased the concentrations of fructose, glucose, total soluble sugar, total antioxidant capacity, total phenols, total flavonoids, ascorbic acid and calcium in the edible part of vegetables, but decreased the concentrations of protein, nitrate, magnesium, iron and zinc.

The projected increases in atmospheric CO_2 concentration will cause a larger nitrogen uptake by the crop, and thus requires larger fertilizer applications (Dong et al., 2018b, 2018c). Changes in climate may also change losses of nitrogen through leaching or gaseous losses with the direction of change depending on the specific CCs at a location. This may also lead to changes in the demand for fertilizer (Bindi and Howden, 2004). In screenhouses atmospheric CO_2 might have a more direct effect. The screenhouse is a semi-closed environment which facilitates strong interaction between crop micro-environment and the outside. Hence, the crop may be directly benefited from the elevated CO_2 concentrations in the atmosphere. On the other hand, CO_2 enrichment might be inefficient due to the porous nature of the cover, and the strong exchange of mass with the outside environment (Tanny et al., 2003).

3.1.2. The impacts of changing precipitation patterns

In Northern Europe, precipitation patterns shift with an increase of rainfall in autumn, winter, and spring, and a decrease in summer, during the major growing period when water is needed in large quantities (Jacob et al., 2014). Moreover, in certain regions the spatial distribution of rainfall is changing due to CC effects, thus imposing water shortages in certain regions. With irrigated horticulture requiring large amounts of water, this will ultimately lead to more competition between water users (Bisbis et al., 2018a,b). If growers fail to sustain adequate irrigation because of water shortage, plants will experience drought stress, which might result in complete crop failure (Gruda, 2009). In a study on the effect of CC on agricultural production of winter wheat and tomato in the Mediterranean region, Saadi et al. (2015) indicated that during the time span between the years 2000 and 2050, an overall reduction of annual precipitation of 39.1 ± 55.1 mm and an increase of air temperature of 1.57 ± 0.27 °C (from 0.84 to 2.31 °C) are predicted relative to values in the year 2000. The consequent increase of annual reference evapotranspiration is 92.3 ± 42.1 mm (6.7%). However, the length of growing season is anticipated to shorten; hence, the crop evapotranspiration is expected to be reduced by 6 and 5% for wheat and tomato, respectively, and the net irrigation requirements under optimal water supply may decrease by 11% for

Table 1
Some sources used in present paper, with few examples of quoted articles.

Year	Number of references	Article examples	Journal, volume
2019	3	Impacts of protected vegetable cultivation on climate change and some adaptation strategies for a cleaner production – A review Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: A review	J. Clean. Prod. 225 Sci. Total Envir. 650
2018	9	Identifying the key impact factors of carbon emission in China: results from a largely expanded pool of potential impact factors Potential impacts of climate change on vegetable production and product quality—a review. Adapting to climate change with greenhouse technologies. Effects of elevated CO_2 on nutritional quality of vegetables – A review Climate change and interconnected risks to sustainable development in the Mediterranean	J. Clean. Prod. 175 J. Clean. Prod. 170 Acta Hortic. 1227 Front. Plant Sci. Nature Clim. Change 8
2017	4	Trends in scientific research on climate change in agriculture and forestry subject areas (2005–2014) Innovations in greenhouse systems – energy conservation by system design, sensors and decision support systems	J. Clean. Prod. 147 Acta Hortic. 1170
2016	4	Protected cultivation as adaptive response in climate change policy: The case of smallholders in Northern Ghana Elevated CO_2 impacts bell pepper growth with consequences to *Myzus persicae* life history, feeding behaviour and virus transmission ability	Journal of Emerging Trends Econ. Man. Sci. 7(5) Sci. Rep. 6
2015	10	Protected crops – recent advances, innovative technologies and future challenges Climate change and Mediterranean agriculture: Impacts on winter wheat and tomato crop evapotranspiration, irrigation requirements and yield	Acta Hortic. 1107 Agric. Water Man. 147
2014	7	The potential of a confined closed greenhouse in terms of sustainable production, crop growth, yield and valuable plant compounds of tomatoes "Sustainable energy greenhouse" Results of the project: Reduction of energy consumption and energy storage in aquifer Management of nitrogen fertilizer application, rather than functional gene abundance, governs nitrous oxide fluxes in hydroponics with rockwool Overwintering potential of the invasive leafminer *Tuta absoluta* (Meyrick) (Lepidoptera: *Gelechiidae*) as a pest in greenhouse tomato production in Western Europe.	J. App. Bot. Food Qual. 87 Acta Hortic. 1037 Plant and Soil 374 J. Pest Sci. 88
2013	3	Microclimate moderates plant responses to macroclimate warming.	Proc. Nat. Acad. Sci. USA 110
2012	7	An overview of climate and crop yield in closed greenhouses Effects on microclimate, crop production and quality of a tomato crop grown under shade nets. Strawberry production in forced and protected culture in Europe as a response to climate change.	J. Hort. Sci. Biot. 87 Biotech. 87 Can. J. Plant Sci. 92
2011	2	Solutions for a cultivated planet. Simulating the consequences of global climate change on greenhouse tomato production in South-France: Preliminary results.	Nature 478 Acta Hortic. 919
2010	2	Aphids in the face of global changes.	Comptes Rendus Biol. 333
2009	7	Influence of high temperatures on gas exchange rate and growth of eight tomato cultivars under controlled heat stress conditions Do soilless culture systems have an influence on product quality of vegetables? Greenhouse technology for sustainable production in mild winter climate areas: trends and needs Comparison of climate and production in closed, semi-closed and open greenhouses	Europ. J. Hort. Sci. 74 J. Appl. Bot. Food Qual. 82 Acta Hortic. 807 Acta Hortic. 893
2008	5	Innovative technologies for an efficient use of energy Vulnerability of horticultural crop production to extreme weather events New developments in greenhouse technology can mitigate the water shortage problem of the 21st century.	Acta Hortic. 801 Aspects Appl. Biol. 88 Acta Hortic. 767
2007	3	Effects of a shading screen on microclimate and crop water requirements	Irrig. Sci. 25
2006	6	Characteristics of climate variations affected winter solar greenhouse production in east of Guanzhong areas of Shaanxi province Quantification of the growth response to light quantity of greenhouse grown crops	Chin. J. Agromet 3 Acta Hortic. 711
2005	8	Airflow patterns through roof openings of a naturally ventilated greenhouse and their effect on insect penetration New developments of energy-saving greenhouses with a high light transmittance Closed greenhouse: a starting point for sustainable entrepreneurship in horticulture Impact of environmental factors on product quality of greenhouse vegetables for fresh consumption. The energy balance and energy-saving measures in greenhouse tomato cultivation The solar greenhouse: state of the art in energy saving and sustainable energy supply.	Bios. Eng. 92 Acta Hortic. 691 Acta Hortic. 691 Crit. Rev. Plant Sci. 24 Acta Hortic. 691 Acta Hortic. 691
2004	1	Challenges and opportunities for cropping systems in a changing climate. "New directions for a diverse planet".	Proc. 4th Inter. Crop Sci. Cong.
2003	4	Temperature gradients in a partially shaded large greenhouse equipped with evaporative cooling pads.	Bios. Eng. 85
2002	4	The effect of periods of high temperature and manipulating fruit load on the pattern of tomato yields. Consequences of climate change for European agricultural productivity, land use and policy. Agricultural sustainability and intensive production practices.	J. Hort. Sci. & Biotech. 77 Eur. J. Agron. 16(4) Nature 418
2001	2	SE - Structures and environment: Vertical temperature and humidity gradients in a naturally ventilated greenhouse.	J. Agric. Engin. Res. 78
2000	2	Effect of CO_2 enrichment on yield of some vegetables grown in greenhouses.	Acta Hortic. 534
1999	2	Heat transfer modeling of screenhouses	Solar Energy 65
1998	2	Crop evapotranspiration - Guidelines for computing crop water requirements.	FAO Irrigation and drainage 56
1997	1	Natural ventilation performances of six greenhouse and tunnel types.	J Agric. Engin. Res. 67
1992	1	Evapotranspiration in greenhouses with special reference to Mediterranean conditions.	Acta Hortic. 335
1987	1	Review: CO_2 enrichment in greenhouses. Crop responses.	Sci. Hortic. 33
1975	1	Shade-cloth microclimate of soybeans.	Agron. J. 67
Total	100		

Table 2
Impacts of climate change on crop production in protected environments.

Changing factor	Prediction[1]	Impact on yield[2]	Impact on product quality[3]	Impact on agricultural practice[4]	References
Increasing atmospheric CO2	Values between 442 ppm (RCP2.6) and 540 ppm (RCP8.5) are predicted by mid-century relative to 1986–2005	**Advantage:** Yields increase with more CO2, especially in screenhouses and reduces input costs for CO2 enrichment	**Advantage:** Increased sugar, antioxidants, ascorbic acid and calcium in vegetables **Disadvantage:** Decreased protein, nitrate, magnesium, iron and zinc.	**Disadvantage:** Larger nitrogen uptake by the crop, requires larger fertilizer applications and may lead to changes in fertilizer demand	1. IPCC (2013) 2. Tanny et al. (2003) 3. Dong et al. (2018a) 4. Dong et al. (2018b,c), (Bindi and Howden, 2004)
The impacts of changing precipitation patterns	The spatial and seasonal distribution of rainfall is changing. In Northern Europe, precipitation patterns shift with an increase of rainfall in autumn, winter, and spring, and a decrease in summer.	**Disadvantage:** Yield loss up to crop failure may result from water shortage in summer. Increased cloud sky-cover causes yield loss. 1% of light reduction causes about 0.5–1% of yield loss in vegetables and ornamentals.	**Disadvantage:** Low light intensity adversely affects plant performance and product quality. High humidity causes mildew, *Botrytis*, grey mold, and reductions of product quality.	**Disadvantage:** Higher crop transpiration at warmer temperatures and more wet days increase the need for humidity control. **Advantage:** Irrigation requirements may decrease in protected environments.	1. Jacob et al. (2014) 2. Gruda (2009), Marcelis et al. (2006) 3. Gruda and Tanny (2014, 2015), Bisbis et al. (2018a,b) 4. Bisbis et al. (2018a,b), Saadi et al. (2015).
The impacts of high summer temperatures	Increases of 1 °C (RCP2.6) – 2 °C (RCP8.5) in global mean temperature are expected until mid-century, relative to 1986–2005, causing longer and more frequent heat waves and temperature extremes	**Disadvantage:** Heat causes erratic yields and increased wastage.	**Disadvantage:** Uneven ripening, soft fruit, poor/late fruit set, delayed ripening, blossom-end-rot and sunburns on vegetable fruits, e.g. tomatoes.	**Disadvantage:** Compression of harvest dates and difficulties in predicting cultivation sequences, particularly in crops that require continuity of supply.	1. IPCC (2013) 2. Adams and Valdés (2002) 3. Gruda (2005) 4. Collier et al. (2008)
The impacts of elevated temperatures on pests and diseases	Higher temperatures reduce winter mortality of insects. Associated variations in wind speed and direction might affect insect penetration into screen-/greenhouses.	**Disadvantage:** Pests and diseases cause substantial yield losses, e.g. up to 100% by *Tuta absoluta*.	**Disadvantage:** Pests and diseases can make products unmarketable. Molds could occur more frequently in cool regions and less in warm regions, altering mycotoxin content in fruits.	**Disadvantage:** Earlier and stronger infestations, with more generations and new species.	1. Hullé et al. (2010), Teitel et al. (2005) 2. Krechemer and Foerster (2015) 3. Van de Perre et al. (2015). 4. Hullé et al. (2010), Van Damme et al. (2014)
Climate simulations for greenhouse horticulture	Modeling approaches were used to simulate effects of projected external temperature and atmospheric CO_2 concentration, as well as internal greenhouse climate and yield (in Japan).	**Advantage:** Winter tomato yield increased by 28% in 2050 compared to 1995 due to higher temperatures and CO_2	Not simulated	**Advantage:** A decreasing demand for greenhouse heating was observed through simulations.	1., 2., 3., 4. Tsutsumi et al. (2015)

Superscripted reference numbers (e.g. [1, 2, 3]) link prediction and impacts with references (last column).

wheat and 5% for tomato. Protected environments restrain the effect of external weather conditions; hence, these changes are expected to be lower for greenhouse plants.

If precipitation will increase in winter, winters will probably be associated with increased sky-cover, unless the main share pours down as short events of heavy rainfall. During the cold season the low amount of solar radiation is already the main limiting factor for production, besides the short days. Low light intensity adversely affects plant performance and product quality (Gruda, 2005; Gruda and Tanny, 2015). In northern latitudes, e.g. the Netherlands, solar radiation is a limiting factor and it was estimated that 1% of light loss causes about 0.5–1% of yield loss in vegetables and ornamentals (Marcelis et al., 2006). A study in China (Ge and Zhang, 2006) examined effects of CC during the years 1963–2001 on production in the Chinese solar greenhouse system. The results showed that the extreme minimum air temperature, fog and full cloudy days had an increased trend in winter. However, the trend of climate variations in the north and south of the Weihe River was different. Consequently, the recommendations were to promote the greenhouse production for vegetables and fruits in Dali County, and reduce the greenhouse production in the areas along the Weihe River.

3.1.3. *The impacts of high summer temperatures*

Climate change scenarios predict an increase of 1 °C (RCP2.6) – 2 °C (RCP8.5) in global mean temperature until the middle of this century, relative to 1986–2005 (IPCC, 2013). This implies that summers in Western Europe will be characterized by longer, and more frequent heat waves, with unprecedented temperature extremes (IPCC, 2013). For the Mediterranean, a review by Cramer et al. (2018) has indicated that the region has already suffered a temperature rise which is higher by 0.4 °C than global average and according to future projections, until the end of the century, increased temperature may reduce summer precipitation by up to 30%, and increase irrigation demand by up to 18% in some regions. High temperatures and unpredictable weather events can cause erratic yields and increased wastage, even in protected cops. The reason could be of plant physiological nature, e.g. for tomatoes due to uneven ripening, soft fruit, poor/late set and delayed ripening of truss varieties (Adams and Valdés, 2002), or due to difficulties in predicting crop cultivation sequences (Collier et al., 2008). Moreover, heat stress at flowering can inhibit fruit-set and can later cause blossom-end-rot (BER) and sunburns on fruits (Fig. 1) (Gruda, 2005; Abdelmageed and Gruda, 2009), thereby decreasing yield, and further increasing the share of waste products (Bisbis et al., 2018a). Crops which require continuity of supply, e.g. leafy vegetables, are particularly vulnerable to extreme weather events. Normally these crops rely on a combination of successional plantings and appropriate genotypes for reliable scheduling. Greater

Fig. 1. Climate change has different faces. Examples: high temperatures, sometimes coupled with drought stress can drastically reduce the product quality of vegetables, accompanied with external symptoms such as (a) blossom-end-rot of tomatoes, and (b) sunburn of Bell pepper, respectively; (c) new pests and diseases, as for instance *Tuta absoluta*, before only a problem in warm areas, is recently dispersed in temperate regions as well (photos: Gruda, private collection).

fluctuations in temperature may result in a compression of harvest dates (Collier et al., 2008).

3.1.4. The impacts of elevated temperatures on pests and diseases

The changing climatological framework will not only affect vegetable crops, but will also influence life cycles, and reproduction rates of insect pests. With increasing global temperatures, winter mortality rates of insects will be reduced, allowing for earlier and stronger infestations, with more generations per year, e.g. aphids, and new species spreading, e.g. *Tuta absoluta* (Hullé et al., 2010; Van Damme et al., 2014; Bisbis et al., 2018a) (Fig. 1). Increasing atmospheric CO_2 can, furthermore, impact on plant-insect interactions, by altering the feeding quality of the host plant, which either reduced insect health or increased infestation intensity, depending on the involved species (Dáder et al., 2016). Although the current climate models do not contain wind prediction, changes in wind speed and direction are likely to have a strong influence on pest and disease occurrence and spread (Collier et al., 2008). For example, in a naturally ventilated greenhouse in which pepper was grown, Teitel et al. (2005) showed that whiteflies population was higher near the roof opening through which wind penetrated into the greenhouse. This suggests that variations in wind speed and direction, due to CC, might affect insect penetration into greenhouses.

Besides securing food supply, an important aspect of human nutrition is food safety. As a consequence of global warming, alternaria mold, might occur more frequently in cool regions e.g. Poland and less in warm regions e.g. Spain, ultimately altering mycotoxin content in fruits as, for instance, Van de Perre et al. (2015) showed in tomato. Due to the temperature increase, winters are becoming increasingly milder (Bisbis et al., 2018a). Warm temperatures in winter usually result in higher rates of crop transpiration, which may decrease the vapor pressure deficit in the greenhouse very rapidly. Increasing winter precipitation with more humid days would aggravate the situation even more. This trend in the winter reveals the need for more effective greenhouse humidity control in the future, in order to avoid phytosanitary problems such as mildew, botrytis, and grey mold, and other reductions of product quality (Gruda and Tanny, 2014; Bisbis et al., 2018a, 2018b).

3.1.5. Simulations of climate change impacts on greenhouse horticulture

Most impacts discussed in the current review were concluded from studies of vegetables grown in adverse climate conditions, elucidating the possible problems to be expected according to the predicted climatic changes. Simulation studies on the influence of CC on the greenhouse internal micro-climate remain scarce. However, to capture the full extent of climatic change these simulation studies are of utmost importance. To our knowledge only one such study was carried out. Tsutsumi et al. (2015) simulated the impact of CC on greenhouse tomato production in Japan by 2050. Various modeling approaches were used to simulate projected external temperature and atmospheric CO_2 concentration, as well as internal greenhouse climate and tomato yield. Results showed that frequency of heat stress events would increase in summer of 2050 compared to 1995, resulting in lower growth rate of tomato in 2050. On the other hand, in winter, tomato yield would increase with decreasing heating demand in the 2050's thanks to the higher atmospheric temperature and CO_2 concentration. In total, tomato yield would increase by 28% in 2050s compared to 1995, since the positive effect of higher CO_2 concentration in 2050 would overwhelm the negative effect of more heat stress in 2050s under conditions without CO_2 injection. Tsutsumi et al. (2015) suggested that in order to make quantitative analysis more precise, models have to be calibrated for specific given conditions.

3.2. Some sustainable adaptations to reduce the impact of climate change on protected horticulture

Climate change will increase the frequency of extreme weather events such as heat waves and drought periods; a corresponding general increase in air temperature during winter might give new opportunities. In the following as well as in Table 3, we present some adaptation strategies to meet the challenges of the impact of changes of CC, describing the advantages and disadvantages for each strategy.

3.2.1. Greenhouse production to meet climate change

Global warming will change the framework conditions in agriculture and protecting crops from adverse weather conditions would become a key issue for adaptation. The construction and cover protect from extreme weather, e.g. wind or hail storms, and facilitate the control of environmental factors such as temperature, humidity and radiation. Greenhouses, thus, present good opportunities to control internal climate conditions and become more independent from the outside climate. This is a major advantage over open field production and a powerful tool in coping with CC impacts. It is of interest also for warm climates, such as the Caribbean region (Lawrence et al., 2015) and Africa (Abukari and Tok, 2016; Schreinemachers et al., 2018) where controlled environment was considered as a viable adaptation option for mitigating the threats of CC. According to Lawrence et al. (2015) and Schreinemachers et al. (2018) controlled environment agriculture has inherent features that mitigate some of the abiotic and biotic threats facing agricultural production under a changing environment. Features include, in part, structural designs, roof and side coverings and growing systems; all of which shelter the crop from adverse conditions, optimize the use of the inputs (in particular land, water) thus resulting in greater yields per unit area (Lawrence

Table 3
Adaptive strategies, to meet the challenges of the impact of climate change on protected cultivation - An assessment.

Adaptive strategies	References
Greenhouse production **Advantages** Control of temperature, humidity and radiation. Shelters for crops from storms and hail. Non-productive lands could produce year-round and high-quality vegetables **Disadvantages** High technology requires high investment and installation costs. High technical skills are required.	Gruda and Tanny (2014) Gruda and Tanny (2015) Gruda et al. (2019)
Reducing water consumption and increasing water use efficiency to meet water scarcity **Screen-/Greenhouses** **Advantages** Reduced wind speed and elevated humidity reduce crop transpiration compared to open field cultivation. The use of shading screens reduces the water demand and increases WUE: inside air in screen-/greenhouses is more humid than outside. Low-cost structures like screenhouses and naturally ventilated greenhouses may reduce the emission of greenhouse gases. Soilless culture systems can be applied to improve water use efficiency. Increasing water saving can be achieved by using crop coefficients for irrigation. **Disadvantages** High technical skills are required. High levels of fertilizer used, e.g. in open systems, runoff and released into the environment. High water amount needed for cooling of greenhouses, e.g. in arid areas.	Stanghellini (1992) Orgaz et al. (2005); Bonachela et al. (2006); Gruda (2009); Kittas et al. (2012); Pirkner et al. (2014); Tanny et al. (2015) Abukari and Tok (2016).
Semi-/closed greenhouses **Advantages** Transpiration is reduced by the higher RH (75–85%), due to reduced opening of ventilation windows. When compared to conventional greenhouses, transpiration of tomato crops was reduced by 29–37%, and consumption of nutrient solution by 30–50%. The reduced water consumption contributed to an increased water use efficiency up to 71%. During the air-cooling process, up to 85% of the total irrigation water condenses on the heat exchangers and can be reused in the nutrient solution. **Disadvantages** Applicable only for high-tech greenhouses with very high investment costs. High cooling investment and running costs for closed greenhouses. Additional need of energy for cooling processes.	Opdam et al. (2005; Teitel et al. (2012); De Zwart (2012); Dannehl et al. (2014)
Enhanced use and improvement of natural and additional light for winter production **Advantages** A sawtooth roof with a 25° pitch on the north side is optimal for light transmission in winter. Aligning the greenhouse in east-west direction has favorable outcomes for light transmission in winter. Anti-reflectance coatings increase light transmission of plastic films or glass cladding by limiting the reflected portion. The winter-light greenhouse increases light transmission by 12%, using larger windows, diffuse glazing with an anti-reflection coating, special energy screens designed for high light transmission as well as a white coating for construction parts for better light reflectance. Supply of additional lighting, especially with highly efficient LEDs where the spectrum is adjustable. **Disadvantages** Not applicable in exiting greenhouses. Favorable outcomes for light transmission in winter are at the cost of light transmission in summer. High initial investment costs. LED-lamps are still expensive. Use of more electricity increases production costs.	Von Elsner et al. (2000); Bakker et al. (2008); Kempkes et al. (2015); Rüther et al. (2016).
Heat waves and required cooling **Cooling and ventilation by screens** **Advantages** Reduces daytime air temperature under the screen. Nighttime air temperature increased under the screens due to less radiative cooling. Leaf temperature of shaded leaves is lower by about 5 °C compared to exposed leaves. Convert solar radiation from direct to diffuse enhancing photosynthesis. **Disadvantages** Different screens have different properties and the properties of screens are not always adequately documented in the literatures. Therefore, it is difficult to find the suitable ones for a certain region. Not exact radiative and aerodynamic properties may result in non-optimal use for a certain crop in a given climatic region. Transmission decreases with time due to dust accumulation.	Healey et al. (1998); Tanny et al. (2009); Kittas et al. (2012); Gruda and Tanny (2014).
Passively ventilated screen-/greenhouses **Advantages** Large greenhouses require roof openings while side ventilation is effective only in smaller greenhouses. Reduction of internal temperature and humidity. Significantly less energy intensive than fan-ventilated greenhouses. Reduce air velocity in regions with high wind speed that may cause damage plans. Pitched roofs with inclinations of 22° and 33° induce larger air exchange rates than flat roofs. **Disadvantages** Sometimes cooling is insufficient and cooling systems based on wet pad or fogging are required. However, the water amount needed for these systems is large. Less effective than active cooling. Cooling effect decreases with solar radiation. Ventilation rate is affected by the area of openings (windows or meshsize) and external wind speed.	Kittas et al. (2003); Arbel et al. (2003); Sase (2006); Teitel and Wenger (2010).
Cooling in semi-closed greenhouses and wise use of CO_2 **Advantages** Crop environment is technically controlled via heat exchangers and heat pumps, allowing a higher degree of climate control. Functions as solar energy collector by harvesting excess heat from the crop environment rather than evacuating it to the outside. Electricity consumption can be limited by using heat exchanging finned tubes, placed under the roof as opposed to air treatment units above or below the crop that require forced ventilation. Temperature lower by 2.5–4.4 °C compared to outside conditions. Vapor, which can be harvested and used for irrigation, condensates on the cold surface when using heat exchangers. Less CO2 required for injection since greenhouse is sealed and internal CO2 rises. **Disadvantages** Use of more electricity increases production costs. Fogging or misting are needed during peak heat loads to avoid excessive use of electricity. Vertical temperature gradients while cooling from below traps the cold air on the bottom of the greenhouse.	Hemming et al. (2008); De Zwart, 2012); Dannehl et al. (2014); Tantau et al. (2015).

(continued on next page)

Table 3 (*continued*)

Adaptive strategies	References
Plant protection in a changing climate	
Advantages	
Pests and diseases can be lowered by using protected cultivation systems with more control over the production environment. In closed and semi-closed greenhouses fluctuations of relative humidity are largely reduced and tomato production is possible with an 80% decrease in chemical plant protection. Dehumidification is realized by cooling with water condensation on the cold surface. Greenhouses should include insect screens installed on the windows to prevent pests from entering, while guaranteeing sufficient air exchange. To protect crops from insects, insect screenhouses are deployed in Mediterranean countries and could extend towards temperate regions as well.	Desmarais et al. (1999); Möller et al. (2003); Opdam et al. (2005); Teitel (2007); De Gelder et al. (2012); Schreinemachers et al. (2018)
Disadvantages	
High investments costs for greenhouses. Air temperature could be higher by 1–3 °C compared to outside, during daytime due to the small mesh size that reduces ventilation rate.	
Breeding stress tolerant cultivars	
Advantages	
Crop breeding creates resistant varieties in terms of thermal time and vernalization requirements, heat shock resistance, drought tolerance, high protein and nutritional levels, resistance to pests and diseases and high irrigation efficiency under conditions of reduced water supplies.	Bindi and Howden (2004); Lankhorst (2017).
Disadvantages	
Breeding process takes long time. Tolerant cultivars have in addition to be productive and have an acceptable product quality. This is not always the case.	

et al., 2015). In addition, year-round and high-quality vegetable crops could be produced, even in non-productive lands with a significant reduction of the number and amounts of agrochemicals used.

Nevertheless, greenhouse constructions might need to be adapted to the new climates. The greenhouse design is strongly influenced by climatic conditions such as snow load, wind speed, or hail (Von Elsner et al., 2000), all of which are expected to change in the future. This gives new opportunities for designing the greenhouse construction, for instance the lower snow load in the future might enable using thinner and more light transmissive glass. On the other hand, increasing incidence of hail could demand for more robust glass to avoid breaking. The inside climate is also strongly influenced by the construction. For instance in Germany, many greenhouses are older than 25 years (Gruda et al., 2009) and lack the necessary climate control capacity required for a more extreme climate. The low ridge height in such constructions causes a rapid heat accumulation in summer resulting in stressed plants (Von Elsner et al., 2000). Ridge height of modern constructions (5–6 m, or even 8 m), allows hot air to rise above the crop environment due to the buoyancy effect. This creates a better temperature-buffer during hot periods, but requires more energy for heating in cold periods. High constructions also give additional space for climate control equipment that will be needed for effective climate control under global warming (Von Elsner et al., 2000). However, the installation of such equipment below the roof and above the plants might increase shading which is usually undesirable in northern countries.

3.2.2. *Reducing water consumption and increasing water use efficiency to meet water scarcity*

Climate change scenarios predict more frequent occurrence of extreme conditions, like drought years, and the uneven distribution of precipitation during the year, which would require higher irrigation efficiency. Increasing water use efficiency and protecting crops from adverse weather conditions become key issues for adaptation. The specifics of screenhouses, naturally ventilated greenhouses, semi-closed and closed greenhouses adaptation tools are presented below.

3.2.2.1. screenhouses. The use of shading screens is known to reduce the atmospheric water demand and enables increase in water use efficiency (Tanny et al., 2015). Hence it may be a feasible solution to cope with CC adverse effects. Tanny et al. (2009) showed that during daytime VPD decreased under the screens, i.e. the air was more humid, due to the lower air exchange rate anticipated below the screen. Similarly, with a shading screen cover over a pepper crop, most of the time the screenhouse air was more humid than outside (Möller and Assouline, 2007). VPD of the shaded plants measured by Kittas et al. (2012) was lower by 50% than for the unshaded plants. Higher internal air mixing ratio (i.e., higher humidity) was also demonstrated for a banana screenhouse in the simulations by Siqueira et al. (2012). The increase in air humidity, and the associated decrease in the vapor pressure deficit, might reduce the irrigation demand of the orchard, and hence lead to water saving which is a significant advantage under changing climate and the frequent occurrence of drought (Siqueira et al., 2012).

Screens induce lower VPD (i.e., increased air humidity) but their effect on air temperature (section 8.2.1.) is not straightforward and depends on additional factors, mainly ventilation rate. The four microclimatic variables of solar radiation, wind speed, air humidity and air temperature, along with additional plant and soil properties, dictate the crop evapotranspiration through the Penman-Monteith equation (Allen et al., 1998). Hence, growing crops under screens may reduce their evapotranspiration through the effects of the screens on microclimate. In recent years several studies have investigated, by direct measurements and modeling, the evapotranspiration of crops under screens. For example, for a table-grape vineyard covered by a light shading screen Pirkner et al. (2014) have shown that crop evapotranspiration under the screen was 66% of the evapotranspiration of a similar crop estimated under outside climatic conditions in the same region. Hence, this study suggested a potential water saving of more than 30%. A similar reduction in evapotranspiration of a banana screenhouse crop compared to open conditions was reported by (Tanny et al., 2012). A sensitivity analysis has shown (Haijun et al., 2015) that this reduction in evapotranspiration is mainly due to the effects of the screen on radiation and wind speed.

Along with water saving through reducing evapotranspiration, farmers are interested in water use efficiency (WUE) namely, the obtained yield per unit of irrigation water. This latter variable has direct economic as well as environmental effects. In an irrigation trial in a large banana screenhouse four irrigation levels were examined, in the range 55%–100% (Tanny et al., 2015). The results showed that the yield obtained at 70% irrigation was statistically the same as that at 100%, hence leading to about 30% increase in water use efficiency. Results from similar experiments in a shaded

apple orchard and a pepper crop in a naturally ventilated greenhouse resulted with water use efficiency increase of about 15% and 20%, respectively (data not published). Hence, low-cost structures like screenhouses and naturally ventilated greenhouses may increase water use efficiency.

Besides adapting the crop environment to CC scenarios, screens may reduce the emission of greenhouse gases, thus directly contribute to reducing future CC.

Similar to screenhouses, growing in a greenhouse can save water due to reduced wind speed and elevated humidity under the cover resulting in reduced evaporative demand and hence crop transpiration (Stanghellini, 1992). This environment presents good opportunity to move from soil to soilless culture systems which further improve water use efficiency, especially in recirculating systems that recapture the drain water for reuse (Gruda, 2009). The lack of bacterial activity in some growing media furthermore reduces CO_2 emissions compared to open field production (Hashida et al., 2014). The largest areas of plastic greenhouses in Europe are found in the Mediterranean countries like Spain. Water is scarce in this region (about 250 mm annually), hence, extensive research was done on evapotranspiration measurements and modeling in naturally ventilated greenhouses in this region (Bonachela et al., 2006; Orgaz et al., 2005). These studies were mainly aimed at improving irrigation efficiency to increase the water saving and farmers profitability. As outcome, the studies provided accurate crop coefficients for irrigation of melon, pepper, watermelon and beans (Orgaz et al., 2005), as well as zucchini and tomato (Bonachela et al., 2006).

3.2.2.2. semi-/closed greenhouses. In spite of reduced summer precipitation in Europe, securing sufficient water supply is essential for vegetable production. Longer drought periods during the main growing season will therefore require a more efficient and sustainable use of water resources, in addition to securing sufficient total amounts of water (Bisbis et al., 2018a). Similar to screenhouses, this is achieved by reducing crop transpiration (Elings et al., 2005). In closed and semi-closed greenhouses, transpiration is reduced by the overall higher RH of around 75–85%, due to reduced opening of ventilation windows (Opdam et al., 2005; Teitel et al., 2012; Dannehl et al., 2014). When compared to conventional greenhouses, transpiration of tomato crops was reduced by 29–37%, and consumption of nutrient solution by 30–50% (Opdam et al., 2005; De Zwart, 2012; Dannehl et al., 2014), with a 9% reduction of fertilizer usage (Grisey et al., 2014). The reduced water consumption could contribute to an increased water use efficiency (WUE) by up to 71% (Dannehl et al., 2014). Another interesting aspect is the possibility to recapture the water transpired by plants and recycle it in the nutrient solution. During the air cooling process, up to 85% of the total irrigation water condenses on the heat exchangers and can be added to the nutrient solution without concern (Teitel et al., 2012). With both, the reduction in total water consumption, and recycling of transpired water, the future challenges of water shortage can be effectively mitigated while not having to accept any trade off with productivity or quality (Van Kooten et al., 2008).

In conclusion, water saving and increasing water use efficiency under screens and naturally ventilated greenhouses are crucial for supplying food under drought years or under variable precipitation levels which do not comply with the cropping season. The use of such structures requires low capital investment by the farmer, hence, such structures are also economic at developing countries, where highly equipped greenhouses are not affordable by the growers. Semi-/closed greenhouses are applicable only for high-tech greenhouses with very high investment costs. In such structures, transpiration is reduced by the overall higher relative humidity, due to reduced opening of ventilation windows. The reduced water consumption and the possibility to extract water from the greenhouse air contribute to an increased water use efficiency (Table 3).

3.2.3. Enhanced use and improvement of natural and additional light for winter production

In Western-Europe, the main constraint when growing crops in winter is the low amount of radiation and the low temperatures. With CC increasing winter precipitation, cloud cover could intensify in future, causing even more shade. Yielding a maximum of light within the greenhouse becomes increasingly important in the future to make use of the additional warmth provided by CC.

The greenhouse construction and cover have the major influence on light transmission. Architectural design, orientation and the nature of the cladding material have an enormous influence on the amount of light that reaches the crop. For instance a sawtooth roof with a 25° roof pitch on the north side is optimal for light transmission in winter (Kempkes et al., 2015). Teitel et al. (2012) have shown that the largest drop in radiation was measured at midday, in the region below the roof openings. This drop was larger by 15–28%, depending on the greenhouse type, than the drop measured at the centreline of the greenhouse span. Beside the design, the orientation of the construction and the cardinal directions influence the light transmission of the greenhouse. Aligning the greenhouse in east-west direction has favorable outcomes for light transmission in winter, however, light transmission in summer is higher when a north-south orientation is applied (Von Elsner et al., 2000; Kempkes et al., 2015).

The optical properties of cover materials, both plastic films and glass are continuously improved. Any significant increase in light transmission primarily depends on innovations in the transparent roof materials (Bakker et al., 2008). Recently, several anti-reflex coatings have been introduced in greenhouse industry. They increase the light transmission in some degree. Promising alternatives are double side coated Anti Reflex glass (Hemming et al., 2006), micro-V treated glass (Sonneveld and Swinkels, 2005) or triple layer systems (Bot et al., 2005, Bakker et al., 2008). Improving the greenhouse light transmission not only has a positive effect on photosynthesis, it also reduces the additional heating power required during winter and thus improves energy efficiency (Elings et al., 2005). Recent studies show that in summer diffuse light is able to penetrate deeper into a plant canopy than direct light. At equal overall transmission, crop production could be improved with covering materials which diffuse the incoming light (Hemming et al., 2006; Bakker et al., 2008). In the Netherlands, the concept of the winter-light greenhouse was developed, using larger windows, diffuse glazing with an anti-reflection coating, special energy screens designed for high light transmission as well as a white coating for construction parts for better light reflectance (Hemming et al., 2017). During winter, this setup increased light transmission by 12% compared to conventional greenhouses (Kempkes et al., 2015).

In the attempt to realise year-round production, the application of artificial light has become a common practice (Bakker et al., 2008). The application of artificial light started in floriculture crops like chrysanthemum and rose, but during the last decade it has also been introduced in fruit vegetables (Bakker et al., 2008) (Fig. 2).

Rüther et al. (2016) showed that exposure to different spectral colors bands can affect the plant growth of petunias. They showed differences in the shoot length depending on the color and duration of light exposure. Particularly strong grown petunias, which were exposed during the day with dark red light at 730 nm. Less extension growth showed petunias under blue (440 nm) and bright

Fig. 2. LED interlighting in production of cherry tomatoes in North Rhine-Westphalia, Germany. LEDs are able to be applied at different wavelengths and since they generate less heat, can be placed close to the plants (Photo Gruda, private collection).

red (660 nm), when LEDs were turned on for 1 h after sunset. Petunias with the least elongation growth were produced with bright red LED exposure during the day. However, it should be kept in mind that such effects can be very different, depending on the species and the variety, and thus the application is difficult on a broad basis.

3.2.4. Heat waves and required cooling

When dealing with natural extremes it helps to draw lessons from natural processes. A study of understory canopy in a forest (De Frenne et al., 2013) has shown that microclimatic effects brought about by forest canopy closure can buffer biotic responses to macroclimate warming induced by CC. In particular, the increase in their presence of warm-adapted species, was attenuated in forests whose canopies have become denser, probably reflecting cooler growing-season ground temperatures via increased shading. Hence, the canopy closure induced by forest trees induced natural shading, in a similar manner like an artificial shading screen. Shading fruit orchards by porous screens, which may reduce noontime air temperature by 1–2 °C (Tanny et al., 2009) may be most significant for maintaining high fruit quality under changing climates. For leafy vegetables, changing to varieties with altered temperature requirements it may be possible to overcome problems in continuity of supply due to CC (Collier et al., 2008).

3.2.4.1. Cooling and ventilation by screens. In a field experiment in an apple orchard covered with screens of different shading levels (0, 16, 30 and 60%, where 0 is control without shading), air temperature and humidity were measured within the trees' foliage. Results showed that during noon air temperature under the screen was lower by about 1.4 °C, and the cooling effect increased with the shading level (Tanny et al., 2009). This daytime air temperature reduction might be significant for the fruit quality, especially under conditions of extreme heat waves which become more frequent under CC conditions. During nighttime the air temperature slightly increased under the screened treatments, by about 0.3 °C, presumably due to some reduction in radiative cooling. A small increase in nighttime air temperature was also found through numerical simulations by Siqueira et al. (2012) in a banana screenhouse.

Cultivating banana orchards under light shading screens became a standard in Israel, due to high yields and water saving (Dicken et al., 2013). Measurements in a banana screenhouse have shown that air temperature was reduced by 1% and relative humidity increased by 8% relative to a nearby external meteorological station (Haijun et al., 2015). The small change in air temperature, as compared to that of the abovementioned apple orchard is attributed to the lower ventilation in the banana screenhouse, with side walls, as compared to the apple orchard that was covered by a shading screen cover on the roof only, without sidewalls, and presumably was much better ventilated. Measurements by Möller and Assouline (2007) in a shading screenhouse (30% black shading screen) covering a pepper crop, have shown that most of the time the internal air temperature was lower than outside. This result was both due to the significant shading by the black screen and the relatively large holes which allowed sufficient ventilation. While in the above studies only air temperature was measured, Kittas et al. (2012) measured both air and leaf temperature of

shaded tomato plants. They showed that although air temperature under the screen was nearly the same as outside, leaf temperature of shaded leaves was lower by about 5 °C than exposed leaves. They noted that the screen was deployed only on the roof which facilitated sufficient ventilation which equalized the inside and outside air temperatures.

The most prominent effect of screens is that they transmit only part of the solar radiation. They also convert part of the radiation from direct to diffuse, which might enhance photosynthesis of large plants where the portion of shaded leaves is significant. For instance, Healey et al. (1998) have shown that radiation use efficiency of several crops grown under shade increased as compared to unshaded control.

3.2.4.2. Cooling in passively ventilated greenhouses. Microclimate in naturally ventilated greenhouses is dictated by the greenhouse type and geometry and can be controlled by opening or closing the vents. An experimental and theoretical study examined the transient response of greenhouse microclimate to vent opening (Teitel and Tanny, 1999). The model was calibrated against experiments in a full-scale greenhouse. The results showed that the reduction of internal temperature and humidity due to ventilation, increased with the height of the window opening, and the wind speed, and decreased with solar radiation. These results are important for greenhouse designers and for prediction of the effect of future changes in climate (wind speed, solar radiation) on internal greenhouse microclimate.

Technologies to cool greenhouse air on hot sunny days have become more important, particularly, natural ventilation systems, which are significantly less energy intensive than fan ventilation systems (Sase, 2006). Natural ventilation systems in greenhouses in mild winter climates consist on either roof or side windows, or a combination of both. The windows can be opened or closed according to the required internal microclimate and the external climatic conditions. The specific ventilation methodology depends on the climatic region, crop and type of structure. For example, in very large greenhouses, side ventilation is not very effective, hence ventilation is mostly based on roof openings. To optimize the location and distribution of the openings over the greenhouse cover, Bournet et al. (2007) utilized Computational Fluid Dynamics tools that allow simulating the ventilation rate under various conditions. Such simulations are also capable of predicting the internal spatial distribution of air temperature at canopy level, a variable which is of utmost significance for crop production, especially under changing climate. If natural ventilation is insufficient to achieve the desired internal air temperature, cooling systems based on wet pad (Kittas et al., 2003) or fogging (Arbel et al., 2003) are used.

3.2.4.3. Air velocity and ventilation rate are the key to effective passive cooling. Screens impose resistance, or drag, to air flow due to the distortion of streamlines around the screen threads. This, in turn reduces the air velocity under the screen and the ventilation rate, or exchange rate between inside and outside. For example, measurements of air velocity at 5 m height in a banana screenhouse by Tanny et al. (2006), have shown that the relation between internal (u_{in}) and external (u_{out}) air velocity was $u_{in} = 0.6(u_{out} - 0.18)$, $R^2 = 0.89$. In a soybean field covered by a shade-cloth Allen (1975) reported a reduction of 67% in air velocity, i.e., $u_{in} \approx 0.33u_{out}$. Reducing air velocity is an advantage in regions with high wind speed which may cause damage to leaves and yield. In addition, a significant effect of screens is in reducing the air exchange rate between inside and outside. Air exchange rate is an important parameter for protected cultivation; sufficient exchange is essential for adequate supply of CO_2 for plant photosynthesis and for the removal of excess heat and water vapor from within the structure. Under conditions of global warming, the need to remove excess heat from within the greenhouse or screenhouse will increase. For a large banana screenhouse Tanny et al. (2006) compared their results with the volume flow rate of a pepper screenhouse (Tanny et al., 2003), as well as with the flow rate obtained by Demrati et al. (2001) in a naturally ventilated banana greenhouse. The flow rate in the banana screenhouse was much larger than those in the banana greenhouse and the pepper screenhouse. This result clearly shows the effect of the screen permeability on air exchange rate. A numerical simulation by Teitel and Wenger (2010) showed that not only the screen type and porosity affect internal air velocity, but also the structural shape of the roof. In particular they have shown that pitched screened roofs with inclinations of 22° and 33° induced a larger air exchange rate through the screenhouse than flat roofs.

Boulard et al. (1997) investigated ventilation in six types of naturally ventilated greenhouses and tunnels. Using neural network analysis, they have shown that ventilation rate is mostly affected by the area of openings and external wind speed. Zhao et al. (2001) investigated the effect of plant height on vertical temperature and humidity gradients in a naturally ventilated greenhouse. Results illustrated that mature plants inhibited natural ventilation thus vertical gradients were larger. When plants were young and small, natural ventilation was more efficient and air mixing reduced the vertical gradients.

3.2.4.4. Cooling of semi-closed greenhouses and wise use of CO_2. The semi-/closed greenhouse is a powerful tool to technically control the crop environment, allowing a higher degree of climate control since the heart of the system is the cooling. Hemming et al. (2008) reported about the use of the greenhouse as solar energy collector based on the principle of heat storage and heat pump system and an efficient heat exchanging system near the crop. A number of technical devices can be used to realise climate control in the semi-closed greenhouse. The concept by Qian et al. (2009) was based on a system that removed the warm and moist greenhouse air by forced ventilation to be cooled in air treatment units (ATU) based on heat exchangers. The ATU served at the same time as dehumidification unit because vapor condensated on the cold heat exchanging surface. After the air conditioning process, the fresh air is returned to the crop (Qian et al., 2009). Different locations for cooling from above or below the canopy were investigated, sometimes with or without distribution ducts below the crop (Campen and Kempkes, 2011; De Zwart, 2012). It was shown that cooling from above does not induce vertical temperature gradients while cooling from below traps the cold air on the bottom of the greenhouse (Tantau et al., 2015) due to density gradients. In contrast to ATUs, finned tube heat exchangers can as well be used for cooling (Dannehl et al., 2014). These finned tubes are placed under the roof to make use of natural convection and the buoyancy effect, which reduces electricity consumption for forced ventilation. With this setup, and the application of fogging during peak heat loads, temperature was decreased by 2.5–4.4 °C compared to outside conditions of 30–33 °C (Dannehl et al., 2014). These results resemble those obtained by Opdam et al. (2005) for closed greenhouses. This temperature decrease compared to the outside temperature is the major advantage as opposed to conventional greenhouses where temperatures are usually higher than ambient. This substantial temperature decrease can be a great advantage, particularly during heat waves, which might be more frequent due to future CC.

All technical improvements that reduce the ventilation requirement of the greenhouse may have the undesired consequence of limiting the natural inflow of carbon dioxide, thereby

limiting photosynthesis and reducing yield (Montero et al., 2009). Therefore, elevated CO_2 had been widely used as gas fertilizer in greenhouse vegetable cultivation, particularly in recent decades when the technology and facility of airtight greenhouses are developed (Mortensen, 1987, Dong et al., 2018a). Stanghellini et al. (2008) recommended an injection of bottled CO_2 up to at least the outside concentration. According to authors, this technology is most likely to be profitable also in simple greenhouses, provided that the injection rate may be linked to the ventilation opening. Since the CO_2 concentration will be increased in the future due to CC, a balance with the outside concentration can be reached through the injection of outside air. This is “wise use” of CO_2 in greenhouse production without high cost investments.

3.2.5. Plant protection in a changing climate

The incidence of pests and diseases can be enormously lowered through the use of protected cultivation systems. Such systems enable producers to gain more control over their production environment (Schreinemachers et al., 2018). However, even though greenhouses are protected environments, pests and diseases can still manage to enter through ventilation windows, or other openings. Closed greenhouses seem to be a suitable solution for this issue because windows remain sealed. This was confirmed by Opdam et al. (2005), who showed that tomato production is possible with an 80% decrease in chemical plant protection. However, due to high cooling investment and running costs the trend is rather towards semi-closed greenhouses, where window opening is only reduced, but allowed. Thus, these greenhouses should include insect screens installed on the windows to prevent pests from entering, while guaranteeing sufficient air exchange (Teitel, 2007).

Apart from the openings, the climate conditions within the greenhouse can favor the spread of pests and diseases in the crop if the environment is not managed properly. High relative humidity may result in fungal diseases such as *Botrytis*, especially when droplets form on the leaves of the crop (De Gelder et al., 2012). The temperature increase associated with CC could enable a more profitable production in winter but with more crop transpiration and water vapor to evacuate. Monitoring and controlling relative humidity during these mild winters becomes an important issue in order to avoid phytosanitary and product quality problems. In closed and semi-closed greenhouses, dehumidification can be realized by simultaneous heating below the canopy and cooling above, thereby dehumidifying the air and giving a more stable climate (Tantau et al., 2015). Generally, humidity is higher in such a setup (at about 80%), but fluctuations of vapor pressure deficit (VPD) could be largely reduced (Qian et al., 2009; Dannehl et al., 2014). This might have favorable outcomes since extremely humid periods, where RH is above 90% are avoided. However, the plants are constantly exposed to higher RH which could favor the expansion of fungi. Qian et al. (2009) observed yield reductions in tomato, due to *Botrytis* mold at the end of the growing season, but without correlation to high humidity. RH was similar, or even lower to that in the control, where plants remained healthy.

To protect crops from insects, insect screenhouses are deployed in Mediterranean countries and could extend towards temperate regions as well. However, in an insect-proof screenhouse in which pepper was grown Möller et al. (2003) reported an increase in air temperature of between 1 °C and 2.5 °C compared to outside, during daytime. Desmarais et al. (1999) demonstrated that for a 50-mesh insect-proof screenhouse, inside air temperature was higher by about 3 °C than outside. Compared to the results in section 3.8.2. about the cooling effects of screens, the above results show that screenhouse effects on air temperature strongly depend on screen type. In shading screenhouses, that are equipped with screens of relatively large hole size, and provide sufficient ventilation, air temperature is usually the same or lower that outside. However, in insect-proof screenhouses, with screens of tiny holes, the ventilation rate is significantly reduced and the internal air is usually warmer than outside. This could lead to tradeoffs between temperature control and insect control when encountering CC and increased occurrence of heat waves.

3.2.6. Breeding

Crop breeding is an adaptive response to CC by the use of both traditional and biotechnology techniques that allow introduction of resistant crop varieties. This approach includes the selection of cultivars with appropriate thermal time and vernalization requirements, heat shock resistance, drought tolerance, high protein and nutritional levels, and resistance to new pests and diseases (Bindi and Howden, 2004). According to the authors, it is important to maintain high irrigation efficiency under conditions of reduced water supplies or enhanced demands. In our opinion, this will be necessary for plastic houses or tunnels without climate control facilities; breeding of fruit vegetable cultivars with higher productivity and a low biomass will help to maintain irrigation efficiency. According to Lankhorst (2017), on average, crops convert only 0.5% of incident sunlight into biomass, whereas some wild plants convert sunlight up to eight times more efficiently. Therefore, more robust and efficient photosynthesis will bring climate-proof, high-yielding food crops within reach (Lankhorst, 2017). Taking into account the large vegetable biodiversity, currently underestimated or undervalued crops have for sure a great potential in new adaptations to climate changes. In addition, the breeding of resilient cultivars to changing pathogen conditions will be an asset. According to Collier et al. (2008), it may be possible to overcome problems in continuity of supply by changing to varieties with altered temperature requirements, however, further research will be required to identify or breed such adapted varieties. Thus, several projects, such as the EU projects TOMGEM (www.tomgem.eu) and/or TOMRES (www.tomres.eu), take place nowadays, in order to select superior tomatoes genotypes with improved adaptability of fruit production to suboptimal environmental conditions, or to combine, novel genotypes with management strategies, having as a goal the reduction of fertilizer application amount and water input, while granting environmental sustainability and economic viability.

3.2.7. Ensuring continuous market supply under climate change

The challenge to supply year-round high-quality horticultural products can be afforded either by growing in high-tech greenhouses or by producing in different locations, whose harvesting periods are complementary (Castilla and Hernandez, 2005). For instance, in the south of Spain, the absence of greenhouse production in coastal areas during the summer months is being substituted by the vegetable produce from screenhouses in the highlands, enabling the year-round market supply (Montero et al., 2009). Similarly, strawberry plants can be propagated under favorable conditions for floral induction in northern areas and then transplanted in southern areas to stimulate floral organ formation and development (Neri et al., 2012). According to Neri et al. (2012), growers are facing CC with innovations in cultivated varieties and cultural techniques, and by the integration of the different production areas, with their specific optimum yield seasons, to continuously fulfill the demands of the market.

3.2.8. Other adaptation possibilities

Apart from factors analyzed above, other important factors are playing a central role in facing sustainable agriculture under CC, e.g. farmer incentives (Tilman et al., 2002) and other political decisions.

Substantially greater public and private investments in technology and human resources are needed internationally, especially in low-income nations, to make agri/horticultural systems more sustainable. Global research expenditures are less than 2% of agricultural gross domestic product (GDP) worldwide (Pardey and Beintema, 2002), being roughly 5.5% of agricultural GDP in developed countries, but less than 1% in developing countries, where most of the increased food demand will occur during the next 50 years (Pardey and Beintema, 2002; Tilman et al., 2002). As Foley et al. (2011) stated, to achieve global food security and environmental sustainability, agricultural systems must be transformed to address the challenges of food production and environmental protection. According to Howden et al. (2007), multidisciplinary problems require multidisciplinary solutions, i.e., a focus on integrated rather than disciplinary science and strengthening the interaction with decision makers. A crucial component of this approach is the implementation of adaptation assessment frameworks that are relevant, robust, and easily operated by all stakeholders, practitioners, policymakers, and scientists.

In addition, well-balanced diets with fruit and vegetable portions are important. Therefore, considering the three-pronged approach of health, diet and emissions (Jeffries, 2015), Gruda et al. (2019, submitted) suggested that year-round fresh vegetables, produced in a sustainable way under covered areas is a central cornerstone to address the future challenges of CC.

4. Conclusions and future outlook

This review presents the impacts of CC on protected cultivation. We showed the different facets of CC and how this affects and will affect greenhouse horticulture in the future as well as innovation-based adaptation strategies to overcome and/or mitigate those impacts. Changes in climate can interact with other greenhouse stressors and affect plant growth, yield and quality of produce. Dealing with CC means coping with extreme heat, seasonally and regionally reduced water availability, elevated humidity, less radiation in winters of temperate regions, and an overall increased pressure by pests and diseases. We focused mainly on the European region pinpointing the differences between the temperate North and the Mediterranean South, and suggested a number of adaptation technologies.

It is our belief that research and development of controlled environment agriculture systems should move forward in two main directions. The first is hi-tech greenhouses, equipped with state-of-the-art active climate control and management systems. Such structures are more feasible for long term production of a specific crop which is under stable and high consumer demand. This is because investment in such structures and the associated control devices is high and hence requires high and stable economical return. The second direction is low-tech greenhouses, based on passive climate control, including naturally ventilated greenhouses and screenhouses. These structures are low cost and will be affordable for regions where agricultural production is less stable economically, and in developing countries where farmers cannot afford high investments. Obviously protected cultivation systems of intermediate level, e.g. greenhouses equipped with a wet pad cooling system, are also feasible, depending on specific crop and regional climate.

Agricultural production in mild winter climates would suffer even higher temperatures than currently, which may cause the increase in the atmospheric water demand and insect invasion to crops. Hence, low-cost structures like naturally ventilated greenhouses and screenhouses will become more popular as an alternative to open-field cultivation. This is because such structures will moderately restrain the effects of CC while keeping the production highly sustainable and environmentally friendly in terms of water and energy consumption. Even in cold climatic regions, like central Europe, such structures might become more feasible as air temperatures would increase compared to the current values and heating demands will reduce due to global warming.

The adaptations that we presented in this review require a new redesigned, multi-disciplinary research approach starting with genetics and crop physiology, through greenhouse engineering, plant phenotyping and modeling, until modern farming management and optimization while ensuring social acceptance.

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